Mapping Mesoscale and Submesoscale Wind Fields Using Synthetic Aperture Radar and AASERT Supplement

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Award # N00014-96-1-0375 and Award # N00014-96-1-0978

LONG-TERM GOALS

Synthetic Aperture Radar (SAR) imagery has shown great promise for depicting the vast array of phenomena that govern the behavior of the ocean mixed layer and marine atmospheric boundary layer (MABL). (Alpers *et al*. 1981; Beal *et al*. 1981; Vesecky and Stewart 1982). The variation of the backscattered intensity field depicted in SAR imagery is directly related to the horizontal distribution of those sea-surface roughness elements having scales generally comparable to the wavelength of the radiation transmitted by the SAR. The local amplitude of the (centimeter-scale for most SAR systems) surface waves that produce this roughness depends on a broad range of oceanic and atmospheric processes and their interactions (*e.g*. Elachi 1987). Because these waves are driven by the surface stress and locally modulated by wave-current interactions and surfactant slicks, SAR images frequently reveal features related to oceanographic processes such as current boundaries, internal waves, or tidal flow over bathymetry, as well as variations in the surface stress due to atmospheric processes.

Our long-term goal in this research effort is to utilize the multiscale information in the atmospheric signatures on SAR images to diagnose a quantitative description of the MABL, including the depth, stability, wind speed, wind direction, sea-surface stress, and buoyancy flux on the mesoscale and submesoscale. Because of its potential for yielding both boundary layer depth and the surface wind field at high horizontal resolution, this application of SAR data represents a significant and innovative advance over most scatterometer algorithms that yield only coarse-resolution wind fields. Moreover, because conventional scatterometry cannot resolve the turbulence structures in the MABL, it cannot be used to diagnose the surface layer stability and so cannot yield wind speed estimates corrected for this important effect.

OBJECTIVES

SAR has the potential to overcome some of the inherent limitations of conventional scatterometry by providing information on the kilometer-scale variability of surface stress. This variability is directly related to the intensity of the primary turbulence structures in the convective MABL via well-known

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**

4. TITLE AND SUBTITLE **Mapping Mesoscale and Submesoscale Wind Fields Using Synthetic Aperture Radar and AASERT Supplement**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Pennsylvania State University,Department of Meteorology,University Park,PA,16802**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002252.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

similarity relationships (*e.g*. Panofsky and Dutton 1984; Stull 1988). These structures, exemplified by three-dimensional convective cells and two-dimensional longitudinal rolls (Woodcock 1975) strongly modulate the sea-surface stress and so leave SAR-detectable footprints on the sea surface in the form of kilometer-scale patterns. By quantitatively analyzing the variability in SAR backscatter intensity wrought by these structures, we are developing methods for determination of boundary layer depth, boundary layer stability, surface layer wind direction, and surface layer wind speed.

APPROACH

We obtain the boundary layer depth directly from the dominant horizontal scale of the SAR backscatter variability using a similarity relationship for the aspect ratio of the horizontal wavelength to boundary layer depth of the associated three-dimensional convective cells (Sikora 1996a, Sikora 1996b, Sikora and Young 1996, Sikora *et al*. 1997).

We obtain the wind direction by noting that the footprints of the MABL inertial subrange turbulence have the same spectral characteristics as the turbulence itself. In particular, the spectral power is greatest when the data series are sampled in the alongwind direction. By rotating a SAR image and conducting a spectral analysis, we are able to determine the orientation associated with maximum spectral power in the inertial subrange. The wind direction is parallel to this rotated image orientation (Winstead and Young 1998).

A primary focus of our research is the development of an iterative algorithm using Monin-Obukhov similarity relationships to relate surface stress estimates to surface layer wind speed (Young and Sikora, 1998b). Monin-Obukhov similarity captures the effect of surface layer stability on the ratio of boundary layer turbulence intensity to mean wind speed. Thus, it is an appropriate tool for relating the degree of kilometer-scale variability in the SAR backscatter intensity to the mean backscatter intensity. By inverting this relationship, we can diagnose the surface layer stability (Monin-Obukhov length) from the ratio of the first and second moments of the SAR backscatter distribution. An iterative solution of similar systems of Monin-Obukhov similarity relations has been done for a number of applications (e.g., Young and Kristensen 1992; Fairall *et al*. 1996). As with other algorithms of this ilk, ours starts with a first guess that is a semi-reasonable value for the surface layer stability. Convergence of the method is not dependent upon our having a particularly accurate first guess of this parameter; both neutral stability and the climatological average stability value have been used successfully in previous studies. A second, quasi-independent method based on the mixed-layer similarity theory for inertial subrange turbulence is also developed. The surface layer stability, surface buoyancy flux and convective velocity scale are also diagnosed from the SAR imagery by using these algorithms (Young and Sikora, 1998b).

We are using the nonlinear convective structure model (Shirer *et al*. 1995, 1996, 1997) primarily to provide the theoretical underpinnings for the refinements of current atmospheric boundary layer similarity theory needed to refine our new iterative algorithm. This task requires that we explore as thoroughly as possible the relevant parameter space (given for example by air-sea temperature difference and surface wind speed). Our highly truncated spectral model, developed under previous ONR funding (Shirer *et al*., 1995, 1996), resolves only the dominant (kilometer-scale) boundary layer eddies, and so fills this role. The essential surface layer physics is incorporated using Monin-Obukhov similarity-based lower boundary conditions linking the model-resolved flow to surface fluxes of momentum and heat (Zuccarello 1994). As demonstrated by Lambert (1995), the model has the ability to produce convectively induced kilometer-scale stress variability patterns resembling those seen on the SAR image studied by Sikora *et al*. (1995). We employ linear analysis of the model solutions to obtain the preferred wavelengths and orientations of the axes of symmetry in the stress patterns for use in improving the similarity theory results as described above. We then employ the nonlinear solutions themselves to refine the relationship between footprint asymmetry and wind direction in the algorithm.

WORK COMPLETED

A paper summarizing results of our algorithm for finding atmospheric boundary layer depth from SAR imagery of the sea surface was published by Sikora *et al*. (1997). George Young developed and tested two similarity-theory algorithms for determining the stability-corrected wind speed, surface-layer stability, and air/sea buoyancy flux from SAR imagery of the sea surface under unstable conditions. A detailed description of these algorithms as well as results of the sensitivity analysis were reported at the 4th International Conference on Remote Sensing for Marine and Coastal Environments (Young *et al.* 1997a), at the 12th AMS Symposium on Boundary Layers and Turbulence (Young *et al*. 1997b), and at the IEEE International Geoscience and Remote Sensing Symposium (Young and Sikora 1998a). A full description of the algorithms, the sensitivity analysis, and the results of its application to SAR data from the Hi-RES experiment have been submitted for publication in *Monthly Weather Review* (Young and Sikora, 1998b). The wind direction finding algorithm has been described and tested on this same data set, with the results forming a companion paper also submitted to *Monthly Weather Review* (Winstead and Young 1998) and presented at the IEEE International Geoscience and Remote Sensing Symposium (Winstead *et al.* 1998). Examination of the meteorological limits of applicability of these flux-finding methods discussed above has been submitted to the American Meteorological Society's 13th Symposium on Boundary Layers and Turbulence (Sikora and Young 1999).

Three papers were presented at the 12th Symposium on Boundary Layers and Turbulence. The first (Young *et al.* 1997b) discussed postdoctoral fellow Todd Sikora's preliminary testing of this algorithm on a small suite of cases from HI RES II. The second (Shirer *et al.* 1997) summarized graduate student David Beberwyk's case study, using the convective structures model, of an ERS-1 overpass of the northern part of the Gulf Stream during the HI RES II experiment. The third (Winstead *et al.* 1997) reviewed AASERT graduate student Pete Winstead's observational study of the SAR signatures of drainage flow exit jets over Chesapeake Bay. This exit jet study is being prepared for submission to the *Journal of Applied Meteorology* in December, 1998.

RESULTS

George Young and Todd Sikora developed a similarity-based iterative solution technique and a quasi-independent similarity-based spectral technique for deriving both the surface layer stability and the stability-corrected scatterometer wind speed from SAR imagery. The sensitivity of these algorithms to uncertainty in the SAR-based estimates of the boundary layer depth was evaluated and found to be negligible for the scatterometer winds, with typical uncertainty in the boundary layer depth leading to wind differences of on the order of one percent. Thus, the algorithms have the capability of correcting scatterometer winds for stability effects even in the face of uncertainty in the boundary layer depth. The surface buoyancy flux estimate that is also produced by these algorithms is rather more sensitive, displaying fractional uncertainties only slightly less then those of the input boundary layer depths. For the magnitude of boundary layer depth uncertainty observed in our preliminary tests at sea, this sensitivity implies air/sea buoyancy fluxes having levels of uncertainty that are comparable with those from the best bulk aerodynamic algorithms. Unlike the bulk aerodynamic algorithms, however, our SAR-based algorithms require no *in situ* data and so may be used where no surface platform or lowlevel aircraft can be deployed. Head-to-head testing of our SAR-based algorithms against *in situ* wind and flux measurements was undertaken using ERS-1 images of the northwest edge of the Gulf Stream from the HI RES II experiment. The results from these preliminary test cases show that the stability correction to the scatterometer-diagnosed wind speed can be significant in the unstable MABL. The algorithms correctly detected the atmospheric surface layer stability transition at the edge of the Gulf Stream. The surface buoyancy flux and convective scale velocities diagnosed from these SAR images via these methods were also robust, with the two quasi-independent methods producing very similar results that are comparable to those observed *in situ*.

David Beberwyk completed the convective structures model development and performed a case study of the convective MABL observed during HI-RES II. As model input he used data taken from the RV Columbus Iselin and the first of two radiosondes launched from the ship. Spectral analysis of a nearly coincident ERS-1 SAR image by Todd Sikora provided the cellular spacing that the model should give. The model was able to reproduce this spacing for a plausible boundary layer wind profile, which had to be chosen because none was measured by the radiosonde, and nonlinear solutions provided estimates of the stress variability produced by the MABL large eddies (Beberwyk 1997; Shirer *et al.* 1997). The resulting stress patterns were oriented within 10 degrees of the 10 *m* current-relative wind in this case, which matched the observations very well. AASERT student John Buzard is using the model to study convective outbreaks observed during January through March 1997. To be able to do so, he has implemented a procedure for ingesting observed wind profiles into the model.

AASERT student Nathaniel Winstead studied an ERS-1 SAR image taken late in the evening of May 9, 1992. This image shows fan-shaped fingers of brightness flowing from the west shore of the Chesapeake Bay. These SAR signatures are perfectly aligned with the creek basins and narrow canyons present along the shore, strongly suggesting a link between the topography around the Bay and the SAR signatures. This coupled with the time of the image suggests that the patterns evident on the SAR are the signatures of exit jets induced by nocturnal drainage flow. A regression analysis was performed to link the size and shape of the individual basins to the length of the SAR signatures (Winstead *et al*. 1997, Winstead 1999). This regression analysis indicates that longer basins with wider gap widths correspond to longer jets. To complement the observational study, a simple, shallow fluid model is developed to simulate drainage flow forced exit jets once they leave their source basins (Winstead 1998). This model allows us to simulate the behavior of these flows over the entire range of forcing values observed in the image. This analysis provides physical insight into the dynamics of these hybrid flows and a basis for the development of a similarity theory relating the physically significant forcing parameters to the characteristic length and speed scales of these phenomena.

IMPACT/APPLICATIONS

Our new quantitative approach will not only provide more accurate wind mapping on a higher resolution than do existing scatterometer algorithms, but it will also allow diagnoses to be performed much closer to strong discontinuities such as coasts and ocean current boundaries. Thus our method offers the promise of mapping winds and boundary layer depth variations within the mesoscale circulations caused by these surface discontinuities. Wind fields as well as maps of boundary layer depth and stability resulting from our studies are expected to yield interesting insights into the mesoscale flow fields near coasts and ocean current boundaries. There is a growing realization from experiments such as HI-RES (Sublette, 1994), that current boundaries lead to mesoscale solenoidal wind circulations and frontal systems just as significant as those associated with coasts. Moreover, our methods yield diagnosed values for the key scaling parameters of both mixed-layer and Monin-

Obukhov similarity theories. Thus, they can support the application of existing similarity theories to diagnose the profiles of the vast majority of turbulence statistics throughout the boundary layer.

TRANSITIONS

We foresee a number of operational uses of our results. First, they will help improve the initialization of horizontally varying fields of boundary layer depth, surface wind, and air/sea temperature difference in operational numerical weather prediction models, especially in data-sparse regions. Second, the high-resolution wind fields could be used to correct synoptic-scale fields that drive global ocean wave models. Third, these high-resolution wind estimates would provide important constraints on coastal remote sensing applications such as the imaging of internal waves or water-mass boundary fronts, as well as absolute surface current measurements using interferometric SAR. Fourth, such products could be useful for near-real-time location of airmass boundaries and other phenomena that vary the boundary layer depth. The method may also prove to have utility for analysis of sea-surface clutter in the SPY-1 radar of the AEGIS system aboard fleet destroyers and cruisers, thereby allowing these ships to monitor the boundary layer depth, surface layer stability, and surface buoyancy flux in real-time with their tactical radar. Finally, the fields we provide might be used as input to radar propagation models (Kerr 1988; Babin 1995).

RELATED PROJECTS

This research follows naturally from our work under the HI-RES ARI project that ended in 1995. The observations taken during HI-RES, particularly the second field deployment, continue to provide valuable data for calibration of the nonlinear convective structures model that was developed as part of the HI-RES project (Shirer *et al*. 1995). The footprint signatures of stable and unstable MABLs that provide the foundation for the current work were first characterized as part of our HI-RES work (Sikora *et al*. 1995; Sikora *et al.* 1997). In fact, it was through interactions at HI-RES workshops that we developed the current collaborative project with our JHUAPL colleagues, Robert Beal and Donald Thompson. Over the long haul, this work may have a significant impact on the ongoing Lockheed/Penn State project to develop techniques for using the SPY-1 radar of the AEGIS destroyers and cruisers to make tactically important environmental measurements without disrupting tactical utilization of the radar.

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